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13. ABSTRACT *(Maximum 200 words)*

Appropriate governing equations for the case of matrix cracking with debonding with friction along the debond have been derived. The variational approach founded on the principle of minimum potential energy is being applied to obtain the numerical results for the stress and displacement fields. On the basis of the Irwin-Kies compliance calibration formulation and the strain energy release rate criterion, the fracture analysis of the matrix crack is carried out. For the matrix crack configuration with interface debonding with friction, the critical loads have been obtained as a function of crack size and interface debond length to assess the competition between the matrix cracking and interface debonding modes. We have also completed static tests on transverse flex specimens to study the cracking behavior along and transverse to fiber direction in continuous and hybrid ceramic matrix composites. This work has been extended to include fiber pullout in model ceramic matrix composites and multiple cracking in laminated brittle matrix composites.

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FINAL REPORT

July 1, 1995 - June 30, 1998

AFOSR GRANT# F49620-95-1-0436

PROJECT TITLE: (AASERT -95) ANALYSIS OF NON-AXISYMMETRIC CRACKING IN CERAMIC MATRIX COMPOSITES

PRINCIPAL INVESTIGATOR: Lokeswarappa R. Dharani

INSTITUTION: The University of Missouri-Rolla

DATE: September 30, 1998

ANALYSIS OF NON-AXISYMMETRIC CRACKING IN CERAMIC MATRIX COMPOSITES

2. OBJECTIVES

The objectives of the project are to develop a micromechanics analytical model to characterize the behavior of brittle matrix composites containing initial flaws, specifically as they approach a fiber-matrix interface, and to assess the competition between various failure modes as the matrix crack impinges on the fiber-matrix interface or an interphase region.

3. STATUS OF EFFORT

The work proposed in the original proposal has been completed. We are continuing our efforts on the characterization of ceramic matrix composites and in particular interface characterization of such systems using internal funds.

4. ACCOMPLISHMENTS/NEW FINDINGS

Appropriate governing equations for the case of matrix cracking with debonding with friction along the debond have been derived. The variational approach founded on the principle of minimum potential energy is being applied to obtain the numerical results for the stress and displacement fields. On the basis of the Irwin-Kies compliance calibration formulation and the strain energy release rate criterion, the fracture analysis of the matrix crack is carried out. For the matrix crack configuration with interface debonding with friction, the critical loads have been obtained as a function of crack size and interface debond length to assess the competition between the matrix cracking and interface debonding modes. We have also completed static tests on transverse flex specimens to study the cracking behavior along and transverse to fiber direction in continuous and hybrid ceramic matrix composites. This work has been extended to include fiber pullout in model ceramic matrix composites and multiple cracking in laminated brittle matrix composites.

The results indicate that the modified principle of minimum potential energy (MPMPE) provides an efficient numerical approach to some of the problems which are not amenable to closed form solutions, especially for complicated cracking configurations such as those involving matrix cracking and interface debonding with and without friction. The comparison of strain energy release rates for matrix cracking and interface debonding has been used to asses the competition between the two failure modes. The parametric studies showed that the interface friction can largely increase the level of the critical applied strain for interface debonding and the cracking changes from unstable to stable state. For the experimental effort, the acoustic emission technique is being used to determine the onset of interface debonding and progressive fiber pullout. We also showed that the use of a chevron-notched fracture specimen provides a much stable crack configuration than that is attainable using straight through-the-thick configuration.

5. PERSONNEL SUPPORTED

a) Faculty: Lokeswarappa R. Dharani (PI, No salary support);

b) Graduate Students: Steven B. Haug, PhD Candidate, Forrest W. Flocker, PhD 1996, Joseph W. Terwelp MSME Candidate, Natalie M Dixon, MSAE Candidate, Brian T. Call, MSEMe Candidate;

c) Undergraduate Student: Jason S. Cargill, BSAE 1997.

All the students above are US Citizens.

In addition to those supported by AASERT Grant, an international student (Fangsheg Ji, PhD 1997) supported by internal funds worked on the project and made a significant contribution towards the success of this project. He was not supported under the AASERT Grant.

6. PUBLICATIONS (July 1, 1995 - June 30, 1998)

1. D. R. Carroll and L. R. Dharani, "Elastic Properties of Imperfectly Bonded Short Fiber Composites," Composite Structures, Vol. 35, pp. 195-206, 1996.
2. L. R. Dharani, F. W. Flocker, R. A. Behr and P. A. Kremer, "Analysis of Transparent Glazing Systems Subjected to Windborne Debris Impact", Progress in Advanced Materials and Mechanics (Eds. T. Wang and T-W. Chou), Proceedings of the International Conference on Advanced Materials, August 12-15, 1996, Beijing, pp. 657-662.
3. F. W. Flocker and L. R. Dharani, "Modeling Fracture in Laminated Architectural Glass Subject Low Velocity Impact", J. Materials Science, Vol. 32, pp 2587-2594, 1997.
4. F. W. Flocker and L. R. Dharani, "Modeling Stress Wave Propagation in Laminated Glass Subject Low Velocity impact", Engineering Struct., Vol. 19. No. 10. pp 851-856, 1997.
5. P. Gopal, L. R. Dharani and F. D. Blum, "Fracture Properties of Glass Strand Reinforced Phenolic Composites," Polymers & Polymer Comp., Vol. 5, No. 5, pp. 327-335, 1997.
6. F. W. Flocker and L. R. Dharani, "Low Velocity Impact Resistance of Laminated Architectural Glass", J. of Architectural Engineering, Vol. 4, No. 1, pp. 12-17, 1998.
7. F. Ji and L. R. Dharani and S. Mall, "Analysis of Transverse Cracking in Cross-ply Composite Laminates", Advanced Composite Materials, Vol. 7, No. 1, pp. 83-103, 1998.
8. F. Ji and L. R. Dharani, "Non-axisymmetric Matrix Cracking and Interface Debonding in Unidirectional Brittle Matrix Composites", European J. Mech. A/Solids, Vol. 17, No. 2, pp 253-268, 1998.
9. F. W. Flocker and L. R. Dharani, "Modeling Interply Debonding in Laminated Architectural Glass Subject to Low Velocity Impact", Structural Engineering & Mechanics, Vol. 6. No. 5, pp. 485-496, 1998.

6. PUBLICATIONS (Cont.)

10. L. R. Dharani, F. W. Flocker, R. A. Behr and P. A. Kremer, "Fracture of Laminated Glass Subjected to Low Velocity Impact", Developments in Mechanics (Ed. C. H. Jenkins), Proceedings of the Twenty-fifth Midwestern Mechanics Conference, September 21-24, 1997, Rapid City, SD, pp. 2-10 - 2-12. [EA, REW, R]
11. L. R. Dharani and F. Ji "Dynamic Analysis of Normal Impact of Occupant Head on Laminated Glass", SAE Technical Paper Series 980862, Safety and Material Test Methodologies (SP-1320), SAE International Congress and Exposition, Detroit, MI, February 23-26, 1998.
12. L. R. Dharani, F. Ji and R. A. Behr, "Failure Onset in Laminated Glass Units Subjected to Velocity Missile Impact", Paper AIAA-98-1858-CP, Proc. 39 th AIAA SDM Conference, Long Beach, CA, April 20-23, 1998.
13. F. Ji and L. R. Dharani, "Non-axisymmetric Matrix Cracking and Interface Debonding with Friction in Ceramic Composites", Accepted for Publication, Applied Composite Materials, 1997.
14. F. Ji, L. R. Dharani and R. A. Behr, "Damage Probability in Laminated Glass Subjected to Low Velocity Small Missile Impacts", Accepted for Publication, Journal of Material Science, 1998.
15. P. Raj, F. W. Flocker and L. R. Dharani, "Computer Simulation of Pressureless Sintering Process", accepted for publication, Math. Modeling and Scientific Computing, 1998.
16. R. A. Behr, L. R. Dharani, P. A. Kremer, F. S. Ji and N. D. Kaiser, "Dynamic Strains in Architectural Laminated Glass Subjected to Low Velocity Impacts from Small Missiles", In Review, Journal of the American Ceramic Society, 1998.
17. F. Dong, F. D. Blum and L. R. Dharani, "Effects of Molding Pressure on the Mechanical and Frictional Properties of a Semi-Metallic Friction Materials", being Revised for resubmission to Tribology International,"1998.
18. T. W. H. Wang, F. D. Blum and L. R. Dharani, "Effects of Interfacial Mobility on Flexural Strength and Fracture Toughness of Glass/Epoxy Laminates", In Review, Journal of Material Science, 1998.
19. S. B. Haug, L. R. Dharani and M. A. Hall, "Transverse Fracture Toughness of Unidirectional Continuous Fiber and Hybrid Ceramic Matrix Composites", In Review, Composites Science and Technology, 1998.
20. L. R. Dharani and F. Ji "Dynamic Analysis of Normal Impact of Occupant Head on Laminated Glass", SAE Technical Paper Series 980862, Safety and Material Test Methodologies (SP-1320), SAE International Congress and Exposition, Detroit, MI, February 23-26, 1998.
21. L. R. Dharani, F. Ji and R. A. Behr, "Failure Onset in Laminated Glass Units Subjected to Velocity Missile Impact", Paper AIAA-98-1858-CP, Proc. 39 th AIAA SDM Conference, Long Beach, CA, April 20-23, 1998.

7. INTERACTIONS/TRANSITIONS

Visited Wright Laboratory, Wright Patterson AFB and McDonnell Aerospace in St. Louis to discuss research in fracture of composites and the results of this project.

8. NEW DISCOVERIES, INVENTIONS, OR PATENTS

None since August 1, 1995

9. HONORS/AWARDS

a) Steven Haug was selected to participate in the NASA Space Grant Consortium.

b) Steven Haug received the Jefferson Goblet Award for the Best Student Paper at the 39th AIAA SDM Conference, Long Beach, CA.

c) Natalie Dixon received the Amelia Earhardt Fellowship from the Zoneta International Association.

d) The PI (Dr. Dharani) was selected to receive the UMR Faculty Excellence Award during 1995 and 1996. He was also selected to receive the Outstanding Teaching Award during 1996-97.